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Marine Reservoir Age Variability Over the Last Deglaciation: Implications for Marine Carbon Cycling and Prospects for Regional Radiocarbon Calibrations

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Key Points:
- Significant, regionally consistent ^{14}C reservoir age changes occurred at middle and high latitudes across the last deglaciation
- Northern and southern R-age patterns differ, underlining the role of ocean circulation and/or sea ice linked to the "bipolar seesaw"
- Regional marine calibration curves are proposed as a viable means of improving marine radiocarbon calibration beyond the Holocene

Supporting Information:
- Supporting Information S1
- Table S1

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Abstract Marine radiocarbon dates, corrected for ocean-atmosphere reservoir age offsets (R-ages), are widely used to constrain marine chronologies. R-ages also represent the surface boundary condition that links the ocean interior radiocarbon distribution (i.e., "radiocarbon ventilation ages") to the ocean's large-scale overturning circulation. Understanding how R-ages have varied over time is therefore essential both for accurate dating and for investigations into past ocean circulation/carbon cycle interactions. A number or recent studies have shed light on surface reservoir age changes over the last deglaciation; however, a clear picture of global/regional spatiotemporal patterns of variability has yet to emerge. Here we combine new and existing reservoir age estimates to show coherent but distinct regional reservoir age trends in the subpolar North Atlantic and Southern Ocean. It can be further shown that similar but lower amplitude changes occurred at midlatitudes in each hemisphere. An apparent link between regional patterns of reservoir age variability and the "thermal bipolar seesaw" suggests a causal link with changes in ocean circulation, mixed-layer depth, and/or sea ice dynamics. A further link to atmospheric CO_2 is also apparent and underlines a potentially dominant role for changes in the ocean's "disequilibrium carbon" pool, rather than changes in ocean transport, in deglacial CO_2 change. The existence of significant R-age variability over the last deglaciation poses a problem for marine radiocarbon age calibrations. However, its apparent regional consistency also raises the prospect of developing region-specific marine calibration curves for radiocarbon-dating purposes.

Plain Language Summary Radiocarbon is widely used to date ancient fossil material, including marine shells, reaching back to ~40,000 years. Less well known, is its use as a marine carbon cycle tracer. Both of these applications require knowledge of how the surface ocean's radiocarbon activity has changed over time, which presents a serious challenge. In this study, we demonstrate that the polar regions of the Atlantic Ocean have experienced significant changes in their radiocarbon activity. These are linked to both regional climate change and atmospheric CO_2 fluctuations, and thus serve to emphasize the important role of processes acting at the sea surface, including sea ice variability in particular, in controlling the heat and carbon storage in the ocean. At the same time, by demonstrating regional consistency of marine radiocarbon trends, our results open up the possibility of improved radiocarbon dating of marine material in future.

1. Introduction

Radiocarbon is widely used as a dating tool and as a hydrographic- and carbon-cycle tracer in paleoceanography. However, prior knowledge of the spatial and temporal variability of radiocarbon activity in the ocean's mixed layer (hereafter the "surface ocean") is crucial for both of these applications. For radiocarbon dating, marine radiocarbon ages must be calibrated to calendar ages using a detailed history of atmospheric radiocarbon activity variability and, therefore, "corrected" for their offset from contemporary atmospheric radiocarbon ages (i.e., their "reservoir age") prior to calibration. Alternatively, a global average reservoir age, along with estimates of regional deviations from this average, can be used to "correct" atmospheric radiocarbon ages instead, effectively providing a marine calibration curve. For studies that deploy radiocarbon as a hydrographic- or carbon-cycle tracer, the "reservoir age" of a parcel of water becomes the metric of

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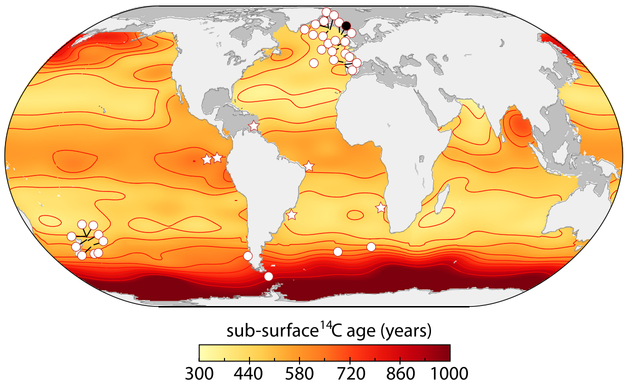

Figure 1. Locations for R-age records included in this study. Black-filled circle indicates the location of the new record from MD04-2929 (this study; 58°56.93′N, 9°34.3′W; 1743 m); white circles indicate the locations of surface R-age records from the Atlantic and Southern Ocean that have been collated in this study. White stars indicate the locations of other sites that are referred to in the text. Shading indicates modern prebomb surface ocean R-age averaged over 100–200-m water depth (Key et al., 2004).

interest in itself. Thus the degree of radiocarbon isotopic equilibration between a parcel of water and the contemporary atmosphere (whether in the mixed layer or the deep ocean interior) will in general reflect three main components: a component due to air-sea gas exchange efficiency and carbon turnover time in the mixed layer; a component due to the transit time from the mixed layer to the water parcel's location in the ocean interior; and a component due to the mixing of different water sources with different dissolved inorganic carbon (DIC) concentrations, different transit times from the mixed layer, and different initial mixed-layer radiocarbon activities. The mixed-layer "reservoir age" therefore represents the surface boundary condition that uniquely links the ocean interior radiocarbon field to the ocean's transport field (e.g., Koeve et al., 2015). If we wish to obtain accurately calibrated radiocarbon dates for chronologies, and if we wish to infer past ocean transports from ocean interior radiocarbon data, we need to know how surface reservoir ages have evolved over time.

A number or recent studies have shed light on surface reservoir age changes over the last deglaciation (Peck et al., 2006; Sikes et al., 2016; Skinner et al., 2010; Skinner et al., 2015; Thornalley et al., 2011; Waelbroeck et al., 2001); however, a clear picture of global/regional spatiotemporal patterns of variability has yet to emerge. Such a picture is likely to be regionally heterogeneous. Here we combine new and existing reservoir age estimates to show coherent but distinct regional reservoir age trends in the subpolar North Atlantic and Southern Ocean, which exhibit diminished amplitude at lower latitudes. This contrasts with the patterns expected due to a "passive ocean" response to changing atmospheric radiocarbon activity (i.e., where the ocean's radiocarbon activity is only driven by the atmosphere's and not vice versa), indicating the involvement of climate and marine carbon cycle change, with an apparent connection to the "thermal bipolar seesaw." Finally, we discuss the implications of these findings for marine radiocarbon age calibrations and raise the possibility of developing region-specific marine calibration curves in order to address emerging challenges for radiocarbon dating of marine sequences in a context of significant and regionally heterogeneous reservoir age variability.

2. Material and Methods

Radiocarbon dates have been performed on monospecific samples of *Neogloboquadrina pachyderma* (left coiling, *s*) from North Atlantic sediment core MD04-2829CQ (58°56.93′N, 9°34.3′W; 1,743 m; MD141 SEQUOIA), recovered from the same location as sediment core DAPC2 (Knutz et al., 2007) on the Rosemary Bank in the northern Rockall Trough (Figure 1). The chronostratigraphy of MD04-2829CQ is based on the alignment of changes in the abundance of the polar planktonic foraminifer species *N. pachyderma* (*s*), relative to the total number of grains in the >150-μm size fraction (Nps%), to regional temperature anomalies inferred from the North Greenland Ice Core Project (NGRIP) ice-core $\delta^{18}O_{ice}$ record (Figure 2), yielding ages on the GICC05 ice-core chronology (Svensson et al., 2008). No correction has been made for the 50-year offset between GICC05 "b2k" ages and "BP" ages, though this level of precision is likely overwhelmed by the much larger uncertainties in correlative ages and radiocarbon dates. The uncertainty in age-tie points is thus conservatively estimated at ~200 years based on the duration of the correlative events and the uncertainty of the GICC05 age scale. These tie points are used to derive a sediment age-depth model using *BChron* (Parnell et al., 2008), which deploys a Bayesian statistical approach to obtain "best guess" and confidence intervals for the sediment age-depth relationship. The resulting age model is used to attribute calendar ages, with uncertainty estimates, to each of the radiocarbon-dated intervals in MD04-2829CQ. The resulting pairs of radiocarbon and calendar ages are then used to derive radiocarbon reservoir age offsets (Soulet et al., 2016) using the *Radcal* program (Soulet, 2015). For comparison, *Radcal* reservoir age offsets were similarly derived for a collection of paired marine (planktonic) radiocarbon and calendar ages from across the northeast Atlantic (Peck et al., 2006; Austin et al., 2011; Freeman et al., 2016; Knutz et al., 2007; Thornalley et al., 2011; Waelbroeck et al., 2001; Waelbroeck et al., 2019), as well as the low-latitude/midlatitude Atlantic (Freeman et al., 2016), the sub-Antarctic and Southern Ocean (Barker et al., 2010; Burke & Robinson, 2012; Diz & Barker, 2015; Siani et al.,

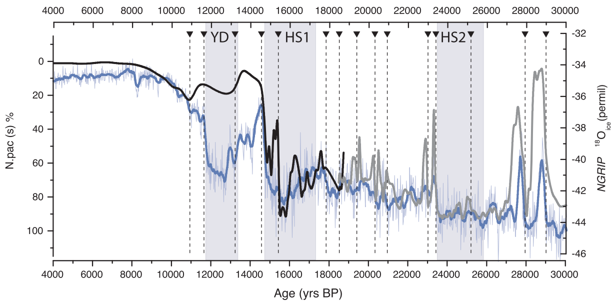

Figure 2. Stratigraphic alignment of *Neogloboquadrina pachyderma* (s) abundance (Nps%) changes with the NGRIP ice core proxy record of temperature (Svensson et al., 2008). Filled symbols and vertical dashed lines indicate location of tie points. Solid black and gray lines indicate Nps% counts from MD04-2829 (black, this study; gray from Scourse et al., 2009). Vertical gray bars indicate the timing of the Younger Dryas (YD) and Heinrich stadials 1 and 2 (HS1, HS2).

2013; Sikes et al., 2016; Skinner et al., 2015; Skinner et al., 2010), and the eastern equatorial Pacific (de la Fuente et al., 2015; Umling & Thunell, 2017). We note that this compilation is not exhaustive (lacking data from the North Pacific and Nordic Seas in particular), though it does serve to illustrate a dominant mode of surface reservoir age variability across the last deglaciation. We report the mode for these shallow subsurface radiocarbon reservoir age offset estimates (hereafter referred to as R-ages) and their estimated uncertainty (based on half of the 95% confidence interval yielded by *Radcal*, which is assumed to be roughly equivalent to one standard deviation). For the subarctic northeast Atlantic, subtropical northeast Atlantic (Iberian Margin), and Southern Ocean, we derive cubic splines for the compiled data (with 95% confidence intervals, assumed to be roughly equivalent to two standard deviations) based on 1,000 random samples of each data set, taking into account the uncertainty in each compiled data point. The locations of the compiled data used for the regional splines are shown in Figure 1.

3. Results

The R-age estimates obtained from MD04-2829CQ are shown in Figure 3 and are in good agreement with others that have been derived for sites in the same region (e.g., Austin et al., 2011; Hall et al., 2011; Knutz et al., 2007; Peck et al., 2006; Thornalley et al., 2011; Waelbroeck et al., 2001). The new data from MD04-2829CQ suggest that generally higher R-ages prevailed in the Rockall Trough region, in the subpolar N. Atlantic, during the last glacial period; ~350 ^{14}C years higher than preindustrial at the Last Glacial Maximum (LGM; ~20 ka BP) and substantially more than this during three millennial perturbations since 30 ka BP that are broadly centered on Heinrich events 2 and 1, and the Younger Dryas. It is notable that the apparent LGM R-age increase relative to preindustrial is only slightly higher than the ~250 ^{14}C years attributable to equilibration at lower atmospheric CO_2 (Galbraith et al., 2015), while the much larger millennial perturbations demand an alternative explanation, most likely linked to, for example, changes in surface stratification, sea ice, mixed-layer thickness, or ocean mixing. In order to place these new data into a wider context, we incorporate them into a compilation of similar R-age reconstructions from a range of sites across the northern northeast Atlantic shown in Figure 4 (i.e., Austin et al., 2011; Hall et al., 2011; Knutz et al., 2007; Peck et al., 2006; Thornalley et al., 2011; Waelbroeck et al., 2019). We have omitted western Atlantic sites from this compilation in order to limit the risk of aliasing different regional patterns of variability. While the cubic spline that is derived from this compilation hardly differs from that based on the smaller subset of data from the Rockall Trough (Figure 3), the scatter in the data is significantly larger. Part of the explanation of this is that the larger compilation incorporates R-ages derived by interpolating chronostratigraphic calendar ages at radiocarbon dated levels rather than attributing radiocarbon dates to secure calendar-age tie points only. Accordingly, we propose that reduced scatter in R-age reconstructions might be obtained if these are inferred via radiocarbon dating exclusively at calendar-age tie points (albeit with a sacrifice in the temporal resolution in available R-age reconstructions unless independent estimates of down-core sedimentation rate changes can be obtained; e.g., Missiaen et al., 2019). Also shown in Figure 4 is a comparison with the R-age "stack" from Stern and Lisiecki (2013). Although this earlier R-age stack (based on benthic oxygen isotope chronostratigraphy) is in broad agreement with our compilation, it also yields generally lower R-age estimates. We suggest that this is due to the fact that the Stern and Lisiecki (2013) R-age stack was based on the tentative (and ultimately incorrect) assumption of zero R-age changes on the Iberian Margin.

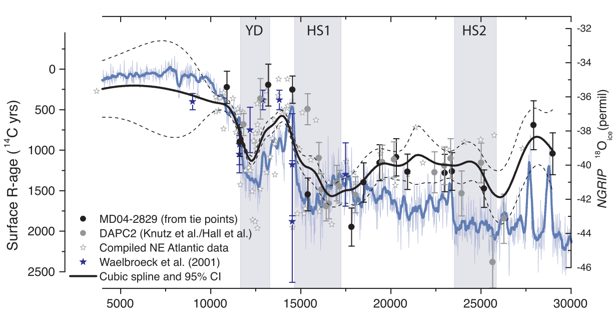

Figure 3. Radiocarbon reservoir ages derived from MD04-2829 compared with data from other nearby locations in the northeast Atlantic. The youngest data point (open star) is an assumed preindustrial value. The solid and dashed black lines represent, respectively, a cubic spline and 95% confidence intervals running through all of the reservoir age data that are plotted. The NGRIP stable isotope record (Svensson et al., 2008), as a proxy for air temperature, is shown to provide a chronostratigraphic reference; vertical gray bars indicate the approximate timing of the Younger Dryas (YD), Heinrich stadial 1 (HS1), and Heinrich stadial 2 (HS2).

If we compare the subpolar North Atlantic with reconstructions from the subtropical northeast Atlantic (Iberian Margin; Freeman et al., 2016), we find a similar pattern of variability, with generally increased glacial R-ages and subtle pulses apparently linked with North Atlantic ice-rafting events

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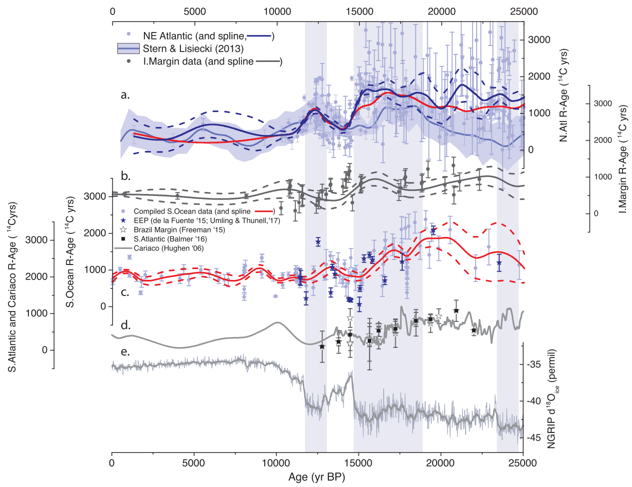

Figure 4. A comparison of reservoir age trends in different regions of the Northern and Southern Hemispheres. (a) compiled R-ages for the northern northeast Atlantic, including data from Waelbroeck et al. (2019-light-blue-filled circles), with cubic spline and 95% confidence intervals (solid and dashed dark-blue lines); the R-age stack and 95% confidence intervals from Stern and Lisiecki (2013) are shown for comparison (light-blue solid line and shaded area). (b) R-ages from the Iberian Margin (dark-gray-filled circles), with cubic spline and associated 95% confidence intervals (solid and dashed dark-gray lines). (c) compiled R-ages from the Southern Ocean (light-blue-filled circles), with cubic spline and associated 95% confidence intervals (solid and dashed red lines); as well as R-ages derived for sites in the Eastern Equatorial Pacific (de la Fuente et al., 2015; Umling & Thunell, 2017; solid blue stars). (d) R-ages from the Cariaco Basin (Hughen et al., 2006; gray line); Brazil Margin (open stars; Freeman et al., 2016); and low-latitude/midlatitude Southern Atlantic (solid squares; Balmer et al., 2016). Note that the Cariaco radiocarbon data are shown on an adjusted chronology (see supporting information). Vertical gray bars indicate the timing of the Younger Dryas (YD) and Heinrich Stadial 1 (HS1).

such as Heinrich Stadial 1 (Figure 4), albeit with an overall subdued amplitude. Notably, the same pattern of variability is not observed in the high latitude Southern Hemisphere shallow subsurface (Barker et al., 2010; Burke & Robinson, 2012; Diz & Barker, 2015; Sikes et al., 2016; Skinner et al., 2015; Skinner et al., 2010), where R-age fluctuations on millennial time scales appear to occur asynchronously (i.e., not exactly in antiphase) with respect to those in the North Atlantic (Figure 4). Again, R-age variability in the subtropical South Atlantic (Balmer et al., 2016; Sarnthein et al., 2015) is found to track that seen at higher subpolar southern latitudes, albeit with a more subdued amplitude. Here we keep separate R-ages derived using standard stratigraphic methods (tephra or signal alignment) and those derived using the "plateau tuning" approach (Sarnthein et al., 2007) in order to permit some kind of cross check on our compiled estimates.

What emerges from the data in Figure 4 is a picture of very large R-age changes since the last glacial period in high (subpolar) northern and southern latitudes, albeit with an apparent "seesaw" between the Northern and Southern Hemispheres, and with more subdued changes occurring at lower latitudes. The apparent link between the observed R-age fluctuations in both hemispheres and the millennial event stratigraphy of the last deglaciation strongly suggests the influence/implication of deglacial climate, ocean circulation and/or sea ice, and carbon cycle changes occurring over this time interval. These associations, and further implications of the observed regionality of deglacial R-age change for marine radiocarbon age calibration, are discussed further below.

4. Discussion

The "asynchronous" millennial-scale patterns of R-age variability observed in the high northern and southern latitudes over the last deglaciation are reminiscent of the thermal bipolar seesaw pattern of polar temperature change recorded in the Greenland and Antarctic ice cores (European Project for Ice Coring in Antarctica community members, 2006). As such, they suggest a causal link between regional climate change and high latitude ocean stratification, which we speculate would most likely operate via halocline development and erosion, and/or sea ice expansion and retreat, during cold and warm periods, respectively. This proposal is supported conceptually by numerical model simulations that demonstrate an important role for sea ice in air-sea gas exchange and reservoir age variability (Eggleston & Galbraith, 2018; Koeve et al., 2015; Schmittner, 2003), and it is consistent with marine and ice-core evidence indicating asynchronous sea ice changes tracking polar temperature anomalies in each hemisphere (Figure 5). Despite these regional differences, a shared global component of variability in R-age variability is also expected due to a "passive ocean" response to changing atmospheric CO_2 levels (Galbraith et al., 2015) and varying atmospheric radiocarbon activity (which is itself a function of variable radiocarbon production rates and carbon cycling; Butzin et al., 2017). Offsets between the expected (i.e., calculated) *global* components and the observed regional trends, shown in Figure, emphasize the component of regional R-age variability that is likely associated with regional climate and ocean circulation change. Notably, this component of past R-age variability will only be captured by numerical model simulations that fully and accurately simulate deglacial ocean circulation and carbon cycle changes. To state this differently, detailed regional reconstructions of reservoir age variability might be used to place useful constraints on numerical model simulations of deglacial ocean circulation changes (e.g., Butzin et al., 2017).

The observation of lower amplitude changes at lower latitudes as compared to higher latitudes is consistent with the stronger and more variable influence of deep mixing in high latitudes (which pushes these regions further from equilibrium with the atmosphere; e.g., Bard, 1988; Butzin et al., 2017). However, the fact that lower latitudes maintain distinct hemispheric "signatures" suggests an additional influence of shallow subsurface flows (sourced at higher latitudes) on the ventilation state of the base of the mixed layer for example.

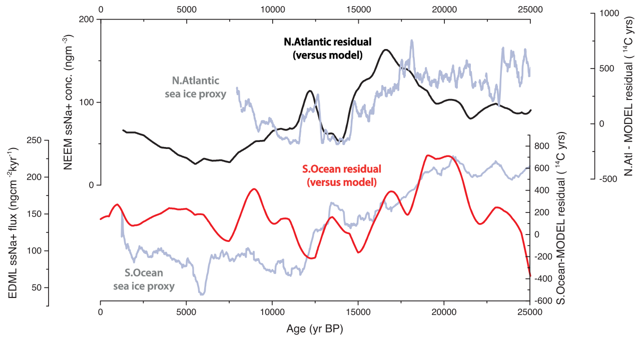

Figure 5. Comparison between regional reservoir age anomalies (i.e., residual between reconstructed and simulated reservoir ages) and ice-core-based sea ice reconstructions for the North Atlantic and Southern Ocean (gray lines). Model outputs are drawn from Butzin et al. (2017), Greenland NEEM ice core ssNa$^+$ fluxes are from Schüpbach et al. (2018), and Antarctic EDML ice core ssNa$^+$ fluxes are from Fischer et al. (2007).

"Downstream effects" of high latitude R-age anomalies have previously been highlighted in the eastern equatorial Pacific (de la Fuente et al., 2015; Skinner et al., 2015), and are illustrated in Figure 4(c). The same approach, imposing high latitude R-age anomalies on a model of modern ocean transports (DeVries, 2014), suggests that the Iberian Margin (like the EEP, also an upwelling region where thermocline waters are brought to the surface) is similarly sensitive to high latitude North Atlantic R-age changes (Supporting Information Figure S1). However, this exercise also suggests that high amplitude R-age changes in the North Atlantic are likely only achievable in the absence of strong lateral transports from lower latitudes via the Gulf Stream and North Atlantic Drift since it is difficult to obtain high R-ages in the open North Atlantic with the modern ocean transports, again in keeping with idealized model scenarios (Butzin et al., 2017). Our observation of significant North Atlantic R-age changes would thus provide evidence for a reorganization of the North Atlantic circulation geometry.

In addition to tracking the influence of high latitude climate/sea ice anomalies and shallow subsurface (e.g., mode water) transport and upwelling, the regionally heterogeneous R-age reconstructions also provide insights into the carbon cycle impacts of past interhemispheric climate change. As illustrated in Figure 6, a tendency for southern high-latitude R-ages to drop is apparent during periods of sustained atmospheric CO_2 rise, consistent with the interpretation of a Southern Ocean source of CO_2 to the atmosphere during deglaciation (e.g., Anderson et al., 2009; Burke & Robinson, 2012; Martinez-Boti et al., 2015; Skinner et al., 2010). The proposed net transfer of carbon from the ocean to the atmosphere would be signaled by a transfer of DIC from the ocean's respired and/or "disequilibrium" carbon pools to the ocean's "equilibrium carbon" pool (and similarly a conversion of nutrients from the "respired" pool to the "preformed" pool; Schmittner et al., 2007; Schmittner & Galbraith, 2008). This would also imply a reduction of the mean "radiocarbon age" of DIC in the deep ocean, consistent with deepwater radiocarbon ventilation records that show a "rejuvenation" of the voluminous deep Southern Ocean and Pacific from the onset of Heinrich stadial 1 (Figure 6). A similar R-age tendency has been reported for millennial events during the last glacial period (Gottschalk et al., 2016), suggesting a consistent mechanism for CO_2 release linked to the thermal bipolar seesaw. Existing deep ocean radiocarbon evidence (e.g., Burke & Robinson, 2012; Sikes et al., 2016; Skinner et al., 2010) has pointed to a particularly large pool of (disequilibrium/respired) carbon in the deep ocean becoming better ventilated in pulses across the last deglaciation (i.e., being converted to "equilibrium DIC"; Figure 6), consistent with evidence for similarly pulsed changes in carbonate chemistry (Martinez-Boti et al., 2015; Rae et al., 2018); however, the deglacial surface R-age changes summarized here emphasize that this process of ventilation was likely mediated to a large extent by processes operating at or near the sea surface. This would underline the role of shallow stratification and/or sea ice affecting air-sea gas exchange, as distinct from vertical mass turnover rates or "upwelling" for example. This observation on its own would further suggest that deglacial changes in atmospheric CO_2 (and the marine radiocarbon distribution at the LGM; Skinner et al., 2017) may have been controlled to a large extent by the "disequilibrium DIC" inventory (Eggleston & Galbraith, 2018) and not the ocean's overturning rate after all.

Finally, the observation of significant and regionally distinct patterns of R-age variability has implications for the calibration of marine radiocarbon dates. The first implication is that past R-age changes cannot be ignored or assumed to be insignificant when generating radiocarbon-based age models, even for locations at relatively low latitudes. The second, stemming from the fact that past R-age changes were apparently linked to major ocean circulation and carbon cycle anomalies, is that "passive ocean" models of past R-age variability (e.g., Butzin et al., 2017; Franke et al., 2008; Reimer et al., 2013), as well as the application of constant *regional* R-age deviations from the global mean (i.e., delta-R values; Stuiver et al., 1986), may yield inaccurate and regionally biased results. In the absence of "perfect" models for carbon cycle (and radiocarbon production) change over the last 50–100 ka, one way to address this challenge might be to construct regional marine radiocarbon calibration curves. These would

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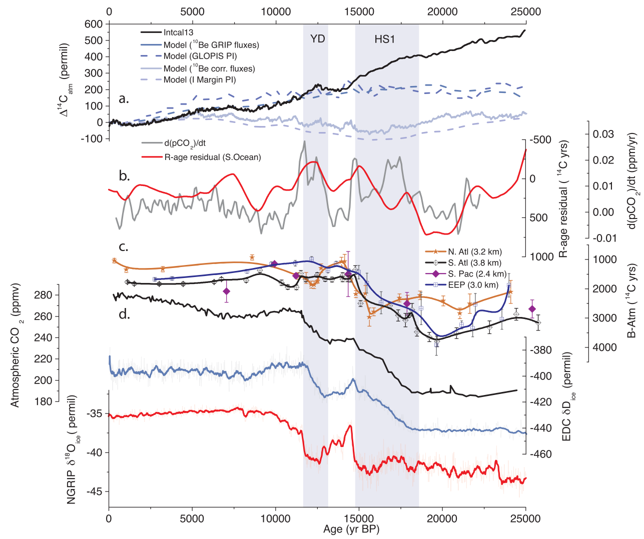

Figure 6. Evolution of Southern Ocean R-ages and the global carbon cycle across the last deglaciation. (a) Reconstructed atmospheric radiocarbon activity based on the Intcal13 data set (Reimer et al., 2013) compared with expected atmospheric activity based on 10Be- and geomagnetic field strength-derived radiocarbon production estimates only (Skinner et al., 2010). (b) Comparison of R-age residuals for the Southern Ocean (reconstructed minus modelled; reflecting nonpassive ocean effects; see text) versus the rate of change of atmospheric CO_2 (Monnin et al., 2001). (c) Deep ocean "radiocarbon ventilation" reconstructions from the North Atlantic (Skinner et al., 2014), South Atlantic (Skinner et al., 2010), South Pacific (Skinner et al., 2015), and eastern equatorial Pacific (EEP; de la Fuente et al., 2015), illustrating a gradual increase in deep ocean ventilation from near the onset of HS1. (d) Atmospheric CO_2 (Monnin et al., 2001) compared with both Antarctic and Greenland proxy-temperature reconstructions (blue and red lines, respectively) all placed on GICC05-equivalent age scales (Lemieux-Dudon et al., 2010). Vertical shaded bars indicate timing of the Younger Dryas (YD) and Heinrich stadial 1 (HS1).

consist of collections of paired marine radiocarbon/calendar age determinations (i.e., as for the R-age estimates presented here; Figure 4). The hope is that relatively few accurate R-age records would be needed to capture the behavior of spatially extensive regimes. Ultimately, numerical model sensitivity tests of the spatial coherence of radiocarbon activity across a wide range of different possible ocean circulation and climate states will be needed to define what constitutes a "region" in this context and to assess to what extent these "R-age provinces" might vary over time. It seems likely that such "R-age provinces" would need to be defined by hydrography rather than by "geography." In this context, a challenge that arises is the possibility for localized seasonal and/or bathymetric biases in the R-ages that are recorded by individual planktonic foraminifer species. Indeed, it must be borne in mind that any R-age derived from planktonic foraminifera (or corals) will necessarily reflect that of the water in which they lived, and not necessarily the "annual average mixed layer," let alone the ocean-atmosphere boundary. Again, numerical models are likely to be invaluable in exploring such issues; though a far larger multispecies radiocarbon data set will also be needed.

By way of illustration, we demonstrate the application of a tentative regional radiocarbon calibration for the Iberian Margin based on a cubic spline fit to our collected R-ages from this region, which we have added to the Intcal13 atmospheric radiocarbon curve (Reimer et al., 2013) to derive a putative Iberian Margin surface ocean curve. Applying this regional calibration curve to a particularly well-dated sediment core that was not included in the compiled data set (SHAK-6-5K; Ausín et al., 2019) yields an age model that is arguably more accurate than that obtained by assuming constant R-ages across the deglaciation. Accordingly, Figure 7 shows how stadial/interstadial transitions recorded in *Globigerina bulloides* $\delta^{18}O$ closely track their counterparts in the independently dated NGRIP Greenland ice-core dust concentration record. The closest stratigraphic agreement is obtained for an age model that was generated by applying core-specific variable R-age corrections obtained from stratigraphic alignment of X-ray fluorescence measurements performed in the same sediment core (MD99-2334 K) to the Hulu speleothem record (Freeman et al., 2016). However, Figure 7 also shows how a very similar chronology can be obtained through the application of a tentative regional "Iberian Margin ^{14}C-calibration

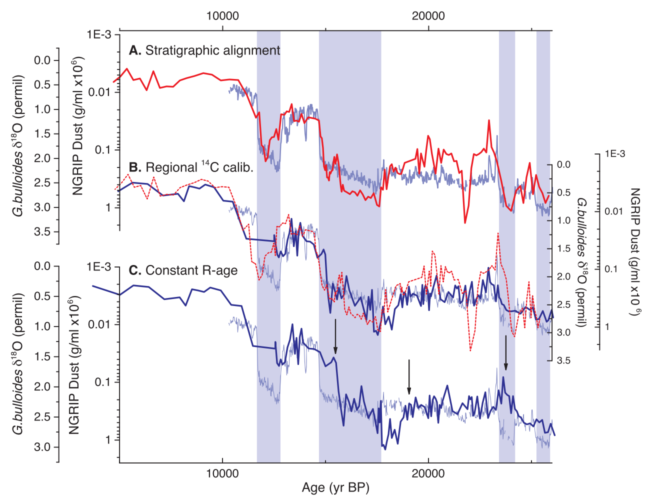

Figure 7. Comparison of chronostratigraphies obtained for *Globigerina bulloides* $\delta^{18}O$ measured in two sediment cores from the Iberian Margin: MD99-2334 K (Skinner et al., 2003, 2014) and SHAK-6-5 K (Ausín et al., 2019). The marine records are compared to the event stratigraphy expressed in the NGRIP dust concentration record (Ruth et al., 2003). (a) Data from MD99-2,334 K on an age scale derived by stratigraphic alignment (Freeman et al., 2016). (b) Data from SHAK-6-5 K (solid blue line) and from MD99-2334 K (dashed red line) on age models that were derived using a tentative "regional radiocarbon calibration" (this study). (c) Data from SHAK-6-5 K on an age model derived using a constant radiocarbon R-age (Ausín et al., 2019), with vertical arrows drawing attention to apparent mismatches between transitions the marine and ice-core records. Vertical shaded bars indicate timing of stadial periods.

curve" to two different sediment cores (SHAK-6-5 K and MD99-2334 K). In contrast, an age model that assumes *constant* R-ages across HS1 and the deglaciation yields stadial/interstadial transitions that clearly precede their presumed counterparts in the NGRIP dust record (arrows in Figure 7), including the cooling at the onset of Heinrich stadial 1 that has been shown to coincide with the onset of increased dust concentrations in Greenland ice (Missiaen et al., 2019).

It is important to stress that while the application of temporally variable R-age corrections, for example, embedded in regional marine calibration curves, should yield more accurate age models, the current precision of this approach leaves significant scope for improvement (for this exercise we have assumed zero uncertainty in the regional calibration calendar ages, which is clearly unrealistic). In addition, it is worth noting that the age biases introduced by ignoring (or not being able to constrain) temporally variable R-ages may not be a major issue in all contexts, though it is clear that they will be very important for the interpretation of, for example, benthic radiocarbon anomalies. We propose that this initial example points the way for future improvements of the radiocarbon calibrations applicable to marine sequences.

5. Conclusions

New and compiled R-age reconstructions show coherent but regionally distinct reservoir age trends in the subpolar North Atlantic and Southern Ocean, with lower amplitude changes occurring at midlatitudes as compared to higher latitudes in each hemisphere. These regional patterns of reservoir age variability track similar patterns in regional climate change (i.e., the "thermal bipolar seesaw"), which suggests a causal link with perturbations to the ocean circulation, mixed-layer thickness, and/or sea ice cover at high latitudes. An indirect link with atmospheric CO_2 anomalies, mediated by changes in ocean-atmosphere CO_2 exchange (and therefore also ocean-atmosphere ^{14}C exchange), is further implied. These findings emphasize that local deviations from the global mean radiocarbon R-age ("delta-R values") have not been constant over time and that local R-age variability must therefore be incorporated into marine radiocarbon age calibrations. One promising approach for addressing this challenge stems from the apparent regional consistency of R-age variability, which could permit the development of region-specific marine calibration curves for radiocarbon-dating purposes. Overall, these results underline the potential importance of large changes in the ocean's "disequilibrium DIC" pool despite its relatively small total inventory in the modern ocean, with implications for the mechanisms responsible for past CO_2 change on both millennial- and glacial-interglacial time scales.

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